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Abstract

The Lower Mekong River has witnessed extremely low water levels over the past few years. There is speculation that the changes are a consequence of the construction and operation of the Chinese cascade dams in the upper part of the Mekong main stream, the Lancang River. Dam construction on upper streams can produce a series of induced effects downstream, particularly in terms of water, sediment, channel and ecological changes. The infilling of the Manwan reservoir in 1992 caused water levels to fall to record lows in various parts of the Mekong River, and sediment concentration values decreased similarly. Analyses of discharge and sediment flux at various gauging stations on the Lower Mekong River have indicated a disruption in water discharge, water fluctuations and sediment transport downstream of the Manwan Dam, after its reservoir was infilled in 1992. Dry season flows showed a declining trend, and water level fluctuations in the dry season increased considerably in the post-dam (1993–2000) period. Monthly suspended sediment concentration (SSC) has also decreased significantly in several gauging stations in the post-dam period. The estimation of sediment flux is challenging since the measurements of SSC were sporadic. Our estimation based on the available data indicated that the areas along the upper-middle and lowermost reaches of the Mekong River have experienced a decline in sediment flux, possibly due to sedimentation in the Manwan Dam. However, the decrease is only statistically significant at Chiang Saen. Areas located in the mid-length of the river show less sensitivity to the operation of the Manwan Dam, as sediment fluxes have remained stable or even increased in the post-dam period.

1. Introduction

In the past decades, dam developments in Asia and Southeast Asia have been increasing steadily, with many of the dams designed for and built on large river systems. The impacts associated with large dam development has been well-researched in developed Western countries, and recently, research on dams in China have also intensified with the construction of the high profile Three Gorges Dam on the Yangtze River, currently the world's largest dam (Chen, 2001; Chen et al., 2001). Common effects of dams cited by research in developed countries include: the modification of flow regimes both upstream and downstream (Williams and Wolman, 1984; Knighton, 1988; Ibàñez et al., 1996; Batalla et al., 2004), the trapping of sediment in reservoirs and disruption of sediment transport downstream (Phillips, 2001, 2003, 2004; Vörösmarty et al., 2003; Walling and Fang, 2003), the reduction of biodiversity due to the flooding of habitat, isolation of animal populations and blocking of migration routes (Gehrke et al., 1995; Kingsford, 2000; Bunn and Arthington, 2002), and in estuarial areas, changes in downstream riparian vegetation and salt wedge dynamics (Wolanski et al., 1996; Friedman et al., 1998). Whilst there have been many studies on the impact of dams on downstream flow and sediment regimes, there have been relatively few on large rivers (apart from studies on the Mississippi in the USA, the Murray Darling in Australia and the Orange Vaal in South Africa), particularly those in Southeast Asia, which possess different hydrological regimes from temperate rivers. Large alluvial rivers in tropical systems are dominated by lateral gradients that can greatly modify the longitudinal pattern of ecosystem processes along the river; and are characterized by highly pronounced biogeochemical dynamics, of which many species are reliant on (Petts, 1990).

The Mekong River region is experiencing dramatic land surface disturbance such as forest clearing, arable land expansion, reservoir construction and water diversion, as a result of rapid population growth and expanding urbanization. Due to its transboundary location, riparian countries are developing different parts of the river basin independently and this has raised many concerns, as the mismanagement of this large resource would cause severe transboundary environmental problems, which could disrupt or result in the loss of livelihoods of people living in the Mekong basin. An ambitious project by China to construct a series of eight large-scale dams in the Upper Mekong (referred to as Lancang Jiang in China) for hydropower exploitation has caused dissension among many Lower Mekong riparian countries. This series of dams, termed as the Mekong Cascade, will be constructed over a 750 km length in the upper basin of the Mekong River (Lancang River) in Yunnan, over a total gradient change of 800 m (Plinston and He, 1999) (Fig. 1). The Manwan Dam was the first to be constructed in the cascades project. The filling of the dam began in 1992, and power generation started in 1993 (Campbell, 2004). In 2003, the second dam, the Dachaoshan was completed and began operations. Construction of the third dam, the Xiaowan, which will be one of the highest dams in the world at 292 m, commenced in December 2001 and is designed for completion in 2012 (IRN, 2002). The reservoirs of both completed and projected dams in Yunnan Province are expected to have a total storage capacity of over 40 km^3, impounding up to more than half of the mean annual runoff of the entire basin, and the entire cascade will have a combined installation capacity of 15 550 MW (MRC, 2003) (Table 1). According to the Mekong River Commission (2003), there are no active considerations to develop hydropower projects that would involve damming the mainstream in the Lower Mekong basin, but some countries have proceeded with independent initiatives for dams in the tributaries, especially large ones leading to the main stream, such as the controversial Nam Theun 2 dam proposed in Lao PDR.

Hydropower dam proponents and builders argue that apart from providing renewable energy, dams aid in mitigating extreme hydrological conditions by controlling the flow of water seasonally, and benefit downstream areas by storing water in the rainy season to reduce flooding and releasing it to alleviate water shortages during the dry season. The Xiaowan Dam, for example, is expected to increase dry season flows by up to 70% as far as 1000 km downstream in Vientiane through the containment of flow in the wet season (IRN, 2002). Despite the advantages purported, it is increasingly apparent that there are major management concerns associated with potential effects on channel and riparian habitats, channel instability and sediment delivery. The large volume of impoundment would likely affect the flood magnitude at the Lower Mekong basin, and have a considerable impact on flows and sedimentation downstream. The Lower Mekong countries are concerned that the construction of the cascade dams in China will reduce downstream water flow and water quantity, while environmental groups and local communities are worried about the effects of these structures on fish species, water fluctuation and river bank collapse (MRC, 2003). Communities downstream of the cascade dams, in Chiang Khong, Thailand, have reported drastic changes in flow velocity, sedimentation, and most acutely, water level fluctuations in recent years. When the reservoir of the Manwan Dam was filled in the dry season of 1992, Thai authorities reported unusually low water levels in the province of Chiang Rai (IRN, 2002; Goh, 2004). A recent report released by the Mekong River Commission (Campbell, 2004) attributed the lower than average flows in the Lower Mekong basin to prolonged drought conditions in the region, rather than as a result of hydropower dam operation in the Upper Mekong. However, it was also noted in the report that the Chinese dams have been contributing to varying levels of water flow along the Lower Mekong, possibly because the water released from the dams are different from and affect the natural flow regime of the river.

Short or intermediate-term changes in water discharge and sediment flux are useful indicators in understanding related phenomena in climate variations or human activities like land use alteration and dam construction (Lu and Higgitt, 1998; Walling and Fang, 2003). Close monitoring of these changes is necessary, although determining reasons behind such regime alterations remains challenging, particularly for large rivers, due to the lengthy hydrological response time and influences from heterogenic or even counter effect human activities taking place around the river (Lu et al., 2003). For the Mekong River, as with many other rivers in Southeast Asia, few holistic studies examining both water discharge and sediment behaviour have been undertaken. In addition, although many have suggested that changes in water discharge and sediment flux have occurred since the operation of the dams in the upper stream of the Mekong River (c.f. Chapman and He, 1996; He and Chen, 2002; Oxfam Hong Kong, 2002; Osbourne, 2004), no systematic analyses of water discharge and estimation of sediment flux has been conducted on multiple gauging stations along the Lower Mekong River. The main purpose of this paper is to examine the extent of influence that Manwan Dam, the first among the upper Mekong cascade dams, has on sediment and discharge behaviour in the Lower Mekong River, through analysis of the following:

(i) Mean annual, maximum and minimum discharge
(ii) Water level fluctuations (mean and day-to-day changes)
(iii) Suspended sediment concentration and sediment flux (i.e. load)

2. Study area

The Mekong River spans a total length of 4800 km and drains an area of 795 000 km^2, with a mean annual water discharge of 470 km^3, making it one of the largest rivers in the world. The headwaters originate at an elevation of about 5100 m in the Tibetan Plateau and flow towards the South China Sea, through Myanmar, Thailand, Lao PDR, Cambodia and Vietnam. By convention, the Mekong River basin is divided into two subbasins: the Upper Mekong basin (24% of total drainage area) and the Lower Mekong basin (76% of total drainage area). While the upper basin is sparsely populated, the lower basin currently supports a population of more than 55 million people, and is expected to increase to 90 million people in 2025. Correspondingly, electric power demand in the whole Mekong region is estimated to increase by 7% annually to 2022, requiring a fourfold increase in current electric generating capacity (MRC, 2003). In view of the future demand and economic viability of hydropower for the Mekong region, numerous projects have been planned by individual countries to tap the hydroelectric potential of the Mekong River; in tandem, research examining the potential environmental and social ramifications of these hydropower projects is also growing steadily.

This study focuses on the Lower Mekong River basin, examining streamflow and sediment records specifically from the following hydrologic stations, located between Chiang Saen in Northern Thailand and Can Tho in the Mekong Estuary: Chiang Saen, Luang Prabang, Vientiane, Nongkhai, Nakhon Phanom, Mukdahan, Khong Chiam, Pakse, Tan Chau, My Thuan and Can Tho (Fig. 1). The northern part of the Mekong

River basin is mountainous with steep-sided slopes; in Luang Prabang, Lao PDR, the Mekong River is marked by relatively sharp bends and flows through a rock-cut channel partially filed with flood alluvium. Reaching the Korat Plateau, the river cuts deeply into the rim of the plateau, forming sheer cliffs above the river before turning eastwards to flow past Vientiane and subsequently along the Lao PDR-Thailand border. This stretch of the Mekong River is characterized by rapids, interspersed with alluvial reaches. Anastomosing of the river occurs at the section where the river reaches the border of Cambodia, with large permanent islands dividing the channels. In Cambodia, the Mekong is connected to the Tonlé Sap (Great Lake) via the Tonlé Sap River. During the dry season, the lake drains into the Mekong via the Tonlé Sap River. As the flood season progresses, the Mekong river rises to above the lake level, and the flow in the Tonlé Sap river reverses and fills the lake instead. At Phnom Penh, the Mekong River separates into two main channels, flowing out to sea through an extensive delta south of Vietnam.

The Lower Mekong study area is characterized by a largely tropical monsoon climate, with two distinct seasons – a wet season from June to October and a generally dry season for the rest of the year. In the lower basin, mean annual precipitation varies from over 3000 mm in Lao PDR and Cambodia to 1000 mm in the semi-arid Korat Plateau in Northeast Thailand (MRC, 2003). The river usually begins rising in May and peaks in September or October, with the average peak flow at 45 000 $m^3 s^{-1}$. Between June and November, discharge from the Mekong would have amounted to about 80% of its total annual discharge. Around November, flows start receding and reach the lowest levels in March and April, at approximately 1500 $m^3 s^{-1}$ (Kite, 2001).

3. Data and methods

This study relies on historical data published by the Secretariat of the Mekong River Commission (MRC), an organization formalized in April 1995 to lead and co-ordinate co-operation in the sustainable development of the Mekong River basin. The formation of the Mekong River Commission replaced the Committee for Coordination of Investigation of the Lower Mekong basin (the Mekong Committee) and the Interim Mekong Committee, which were established in 1957 and 1978, respectively (MRC, 2003a). Annual records of discharge and suspended sediment concentration for the study area were extracted from the series of historical records published by MRC since 1962 (MRC, 2000). The publications tabulated measurements of water discharge, suspended sediment concentration (SSC), water quality and other physical characteristics of a series of gauging stations located along the Lower Mekong River and its tributaries.

The time-period of this study spans 39 years, from 1962–2000. Regular stream flow and sediment measurements only started a few years after the formation of the Mekong Committee, and due to the political volatility in the region, measurements were not taken for several years in parts of Cambodia and Vietnam. Understandably, the use of a shorter time series dataset has limitations in terms of extreme events analysis, which requires a longer range of data. In view of this, our study will focus on the comparison of flow and sediment data before-and-after dam construction. Flow and SSC records from eleven gauging stations (Fig. 2) located on the main stream of the Lower Mekong River were identified for this study, of which records from six stations were used to calculate sediment flux (Chiang Saen, Luang Prabang, Nongkhai, Mukdahan, Khong Chiam and Pakse). The stations were selected based on two main criteria: first, their relative location from one another, ensuring that there was a good coverage of stations along the length of the Lower Mekong River, and second, the completeness of flow and sediment records for the station. Annual SSC and water discharge records were also checked for high correlation before they were used to calculate sediment flux. Table 2 lists the stations meeting the above requirements and the corresponding availability of sediment concentration records. Hydrological and sediment records from stations located on the upper basin of the Mekong River (the Lancang River) in China were not available to the authors.

3.1. Water levels and water discharge analysis

The datasets used for hydrological analysis included gauge height levels [m] and daily discharge [$m^3 s^{-1}$]. Time-series graphs for annual mean, maximum and minimum discharge, and maximum-minimum ratio graphs were constructed to discern hydrological patterns and to evaluate the effects of impoundment on flow in the lower reaches of the Mekong River. Daily fluctuations in water level, represented by gauge height data, were examined for specific years at several stations representing different sections of the Lower Mekong: Chiang Saen, Nongkhai and Pakse. The years chosen for analysis were 1988 (two years into the construction of the Manwan Dam), 1991 (just before closure of the dam), 1992 (closure of the dam), and 1996 (fully operational), 1999 and 2000. In addition, day-to-day changes in water level were also computed for two selected pre- and post-dam years, (1991 and 2000) to further examine the impact of the dam on daily discharge fluxes.

3.2. Sediment concentration and sediment flux estimation

Unlike discharge which was measured daily, measurements of suspended sediment concentration (SSC) were relatively sporadic, ranging from 1–6 times per month. The sampling frequency varied for different time periods: for instance, between the mid-1970s and 1980s, measurements of sediment concentration were not conducted at several gauging stations due to the political unrest in some of these areas. Sediment sampling procedures generally followed USGS guidelines with special modifications for conditions in the Mekong. SSC samples were taken with the U.S. D-49, U.S. P-46 and P-61 point integrating samplers, from 0.30 m below the water surface, in the middle of the main stream (MRC, 2000). Vertical profiles of SSC were not available in the dataset, therefore the sediment flux calculations in our analysis may not represent the actual total suspended sediment load in the river, but are closely indicative.

The estimation of suspended sediment flux (i.e. load) is challenging in the Lower Mekong River, given that many gauging stations do not document relatively long-term sediment concentration measurements. Due to the scarcity of sediment concentration data, estimates of sediment load were based on discrete, instantaneous measurements of suspended sediment rather than continuous data at regular intervals. Hence it is acknowledged that the frequency of sampling does not ensure that all ranges of the flow were sampled. Various studies on sediment load estimation have noted that irregular sampling intervals, discrete data and the exclusion of the bedload component may result in underestimation of sediment discharge during peak flows (Ibàñez et al., 1996; Lu and Higgit, 1999, Phillips, 2004).

The available measurements of the daily SSC were used to develop sediment rating curve, which depicts the statistical relationship between suspended sediment concentration and discharge:

$$C_s = aQ^b \tag{1}$$

where C_s is the instantaneous sediment concentration [mg/l], Q is the instantaneous water discharge [m^3/s] and a and b are the sediment rating coefficient and exponent. The correlation between SSC and discharge (Q) are statistically significant (Table 3). Daily sediment concentration value was estimated using this relation, and sediment load (metric tons/day) was computed from the estimated sediment concentration and the measured water discharge:

$$SL = QC_s \tag{2}$$

There were notable gaps in the sediment record of the Lower Mekong River, where sediment concentration data were unavailable for more than five years. In order to evaluate the impact of dam construction on sediment flux patterns over a more complete timeline and to obtain fairer estimates of mean sediment discharge, sediment concentration measurements extracted from water quality data were also used to calculate sediment load for certain years (Table 2). The correlation between discharge and sediment concentration measurements taken from water quality data were equally high (r^2>0.7). Understandably, sediment concentration data derived from water quality measurements may vary with conventional sediment sampling, partly due to the

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frequency of sampling. Water quality samples (incorporating sediment concentration measurements) are taken once a month while conventional sediment samples usually comprise 12–60 readings per hydrological year, concentrated in the flood season.

4. Results

4.1. Mean annual flows

Mean annual flows of the stations surveyed are shown in Fig. 3. Mean discharge in all stations fluctuated within the usual historical range during both pre- and post-dam periods, from 1962 to 2000, although there were occurrences of larger and sporadic variations. No significant changes were observed in mean discharge along the Lower Mekong River, except at Nakhon Phanom, which registered a statistically significant increase ($p<0.05$) in discharge from the pre-dam period (1962–1992) to the post-dam period (1993–2000) (Table 4). Among the stations surveyed five out of eight experienced the lowest discharge in 1992. The fact that 1992 was not a drought year (Nguyen, 2003) seemed to indicate that the infilling of the Manwan Dam did exert some influence on discharge. Chiang Saen, the nearest station to the Manwan Dam, had the lowest mean discharge, and annual fluctuations in its discharge were smaller compared to other stations downstream. There was evidence of regional variability in discharge behaviour, for example, exceptionally high flood peaks for the years 1966 and 1971 were observed at Chiang Saen, Luang Prabang and stations on the upper region of the Lower Mekong River, but these did not coincide with flood peaks in the lower regions of Khong Chiam and Pakse, which occurred in 1978 and 1981.

4.2. Annual maximum and minimum flows

Annual maximum and minimum flows, or so called extreme daily flows, may be more suitable indicators of land surface disturbances such as land cover or land use changes and reservoir construction (Lu et al., 2003; Lu, 2004). Annual maximum discharge across all stations showed an overall decrease in the pre-dam years, especially from the mid 1980s to early 1990s (Figs. 4a and b). In 1992–1993, a relatively pronounced reduction in maximum discharge occurred in all stations, likely a consequence of the reservoir filling at the Manwan Dam, but thereafter, when the dam began operating, maximum discharges in several stations showed signs of increase, though only Nakhon Phanom registered a statistically significant rise ($p<0.05$). Other studies on the effects of flow impoundment in China (Jialing River, tributary of the Yangtze River) and in Siberia (Yenisei River) also noted similar increases in maximum discharge during the flood season (Chen et al., 2001; Yang et al., 2004)

Analysis of the maximum discharge fluctuations in pre- and post-dam periods (Figs. 4a and b) also revealed that, for the stations located in the upper region, the pre-dam period (1962–1992) was characterized by closely synchronized maximum discharge fluctuations, but after the reservoir infilling of the Manwan Dam started in 1992, the synchronization in peak flows was no longer obvious, with each station generating different hydrological flow patterns. As discharge flowed farther downstream from Nakhon Phanom to Pakse, the irregularity in flow patterns could have been reduced by tributary inflows. Therefore in downstream areas, pre- and post-dam flow patterns and fluctuations were largely similar.

A decrease in annual minimum discharge was observed at stations nearer to the Manwan Dam (Chiang Saen and Luang Prabang) in 1992, and is probably also due to dam infilling, which took place in the dry season of the same year (Fig. 4a). Stations further downstream experienced low minimum flows in 1993, but the flows were within the historical range (Fig. 4b). Again, there was no obvious indication of a change in trend in terms of minimum discharge, apart from Nakhon Phanom, which experienced a significant increase ($p<0.05$) in discharge in the post-dam period (Fig. 4b). The magnitude and frequency of fluctuations in minimum discharge increased after 1992, and synchronization of low flows improved from pre-dam periods. Changes in the seasonal flow regime (i.e. minimum and maximum discharges) are reflected in the ratio of maximum/minimum flows (Figs. 4a and b). Stations nearest to the Manwan Dam (Chiang Saen, Luang Prabang and Vientiane) showed the most distinctive change in maximum/minimum ratios (Fig. 4a), with a clear increase in range and fluctuations from the pre-dam to post-dam period.

4.3. Daily water level fluctuations

Dry season water level fluctuations have been influenced by the operation of the Manwan Dam significantly (Fig. 5). The fluctuations in the pre-dam period were minimal and of a small magnitude; this changed considerably in the post-dam years as water level fluctuations became larger and more frequent. Among the stations examined, the contrast between pre- and post-dam dry season fluctuations was largest at Chiang Saen, the station closest to the dam on the Lower Mekong. Wet season water level fluctuations did not reveal any discernable differences between pre- and post-dam years, and appeared to be unaffected by the operation of the dam (Fig. 5). Analysis of day-to-day changes in water level yielded similar results, with dry season water level changes displaying greater sensitivity in the dam operation period (Fig. 6). The magnitude of the daily water level fluctuations in the dry season in the post-dam period was also augmented relative to pre-dam fluctuations.

4.4. Suspended sediment concentration (SSC)

A declining trend in mean monthly suspended sediment concentration was observed along the entire length of the Lower Mekong River since water quality measurement began in 1985 (Fig. 7). However, the decrease was statistically significant at only three stations, two in the upper part of the river (Chiang Saen and Luang Prabang) and one further down in the Mekong Estuary (Can Tho). At Chiang Saen, sediment concentration patterns reflected closely the construction stages of the Manwan Dam. In the wet seasons of 1986 and 1987, when construction of Manwan Dam began, there were two pronounced peaks in sediment concentration for these two years, after which fluctuations reverted to the historic range. There was a third peak in sediment concentration at Chiang Saen and Luang Prabang in the wet season of 1991, possibly due to the surge of water discharge in that year. When Manwan Dam was closed for infilling in 1992, there was a pronounced reduction in sediment concentration values along the Lower Mekong, especially at Chiang Saen. Stations furthest downstream such as Tan Chau, My Thuan in Vietnam also experienced reductions as a consequence of dam closure, but of a smaller magnitude (Fig. 7).

A comparison of mean sediment concentration values in pre- and post-dam periods revealed that stations located on the middle-upper portion of the Mekong River experienced larger decreases in sediment concentration than stations downstream (Fig. 8). Average SSC values for upstream stations (Chiang Saen to Vientiane) in the post-dam period declined approximately 40% or more, while SSC in downstream stations only decreased slightly from pre-dam values. Vientiane yielded the highest average SSC in both pre- and post-dam periods, and Tan Chau, Can Tho and My Thuan, the lowest. In the pre-dam period, Chiang Saen had relatively high levels of sediment concentration comparable to values at Vientiane, however in the post-dam period, SSC values at Chiang Saen were lower in comparison to Vientiane and Luang Prabang.

4.5. Sediment flux changes

One of the main concerns with dam construction in the Mekong is the influence on suspended sediment flux, because a change in sediment behaviour might be potentially detrimental to the health of the entire river ecosystem. Table 5 presents a summary of pre- and post-dam sediment flux (i.e. load) and corresponding average annual fluxes for the analyzed stations. Comparison of mean sediment fluxes in pre- (1962–1992) and post-dam (1993–2000) periods for each station shows the apparent effects of flow impoundment on sediment fluxes, and downstream persistence of these effects. The sediment loads in four out of six stations have declined since the Manwan Dam began its operations in 1992 (Fig. 9). However, the change in mean sediment load was only statistically significant at Chiang Saen ($p<0.05$). Mean annual sediment load at Chiang Saen, has decreased by more than 50% from 74.1 MT/yr (pre-dam) to 34.5 MT/yr (post-dam). Luang Prabang, the next station after Chiang Saen, has also experienced a similar decline in mean sediment load from 73.0 MT/yr to 47.2 MT/yr. Stations in the middle section produced variable results. The sediment flux at Nongkhai showed very little variation from a pre-dam mean load of 74.4 MT/yr to 76.1 MT/yr in the post-dam period, whereas the sediment flux in Mukdahan has increased from a mean sediment load of 97.5 MT/yr to 131.1 MT/yr (34% increase).

The increase in sediment flux at Mukdahan (34%) suggests several possible processes taking place at the river bank interface. Firstly, more intensive remobilization of alluvial sediment storage could be taking place, possibly through bank erosion; secondly, regional tributaries cutting through mostly agricultural land may transport significant amounts of sediment into the main stream, and lastly, the increase in anthropogenic activities in the floodplain and valleys contribute additional sediment. As with stations located in the upper reaches, stations farthest downstream in Khong Chiam and Pakse also experienced decreased mean sediment loads after 1992.

Kummu et al. (2005) reported similar decreases in post-dam sediment transport at Chiang Saen (68.5 MT/yr to 35.1 MT/yr), Luang Prabang (65.6 MT/yr to 46.9 MT/yr) and Pakse (120.6 MT/yr to 99.2 MT/yr). The variation in estimation of sediment fluxes is attributable to differences in estimation methodologies and the number of sediment sample records. Previously, Milliman and Syvitski (1992) and Roberts (2001) estimated the total annual sediment load of the Lower Mekong River to be 160 MT/year and 150–170 MT/year respectively, with 50% of the load reportedly derived from China (Roberts, 2001; MRC 2003).

5. Discussion

5.1. Impact of the Manwan Dam on water discharge and water fluctuations

From the mean annual discharge trends observed along the Lower Mekong River, it seems that the impact of the Manwan Dam on water discharge was largely restricted to the upper reaches of the river, which experienced more remarkable changes in flow regime than the stations downstream. Batalla et al. (2004) reported similar results on the Ebro River in Spain, with downstream recovery of pre-dam hydrologic regime noticeable in all studied cases, and dam-induced hydrological effects nearly completely attenuated after tens of kilometers and a doubling of drainage basin area.

According to He and Chen (2002), the cascade dams are projected to increase monthly flows at the border between China and Myanmar in the dry season, and decrease flows during the flooding season, and that this would be beneficial downstream in terms of irrigation and navigation development, hydropower transmission and possible flood control through flow regulation by the cascade reservoirs. Our results indicate that the effect of the small scale Manwan Dam on maximum and minimum flows is not obvious. However, the frequency and magnitude of water level fluctuations have been increased considerably since 1992, suggesting that the water level fluctuations have indeed been enhanced by the dam operation. Similarly, a study commissioned by Oxfam Hong Kong (2002) examining the impacts of Manwan Dam also noted that since the dam began operations, daily fluctuation at the base of the dam was 3–4 m on the average, peaking at 6.5 m in 1998. This holds serious implications for the aquatic ecology of the Lower Mekong River. Nevertheless, these fluctuations have been observed mainly in the dry seasons, which may have less detrimental effects on river bank collapses, compared to the fluctuations in the wet season when the water levels are high.

The possibility of the lower Mekong River reverting to its pre-dam hydrologic regime after the completion of all dams in the upper basin (Lancang) remains uncertain, as the contribution of discharge from Lancang forms approximately 16% of the total runoff of the entire Mekong basin, which may not be a considerable volume in terms of the total. However, if we look at the runoff contribution from Lancang in various sections of the lower Mekong: 100% at the China-Laos border, 60% as far downstream as Vientiane, 20% at Pakse , 15–20% in Vietnam and 16% at Phnom Penh (World Rivers Review, 2001), a propagation of dam-induced effects downstream seems likely, given the influence of the Lancang contribution in the middle-lower reaches of the Mekong; these effects could be further augmented by water diversion projects (e.g. the Kok-Ing-Nan Water Diversion Project) and numerous tributary dams (e.g. Pak Mun dam) occurring along the length of the lower Mekong river.

5.2. Impact of the Manwan Dam on sediment concentration and flux

The reduction in sediment load for Chiang Saen is apparently a consequence of the Manwan Dam, which depleted the amount of sediment delivered downstream as a result of siltation in the reservoir. Due to the smaller scale of the Manwan Dam, the influences directly attributed to the operation of the dam tend to be more discernable at stations in the upper region of the Lower Mekong. Moving downstream, the impact of the dam becomes less distinct whilst local contributing factors become more influential, evident in the sediment variability at Nongkhai and Mukdahan.

The extent of Manwan's influence on suspended sediment concentration is evident from the pronounced reduction in average concentration values in the upper mid-stream stations during the post-dam period. In terms of spatial changes in sediment concentration, the Mekong River presents an interesting case because we would usually expect sediment concentration values to decrease consistently in areas immediately downstream of the dam due to sediment trapping, which reduces sediment transport downstream. However, high sediment concentration values in Vientiane and to a lesser extent, Luang Prabang, suggest that the areas surrounding these stations might be contributing considerable amounts of sediment into the Mekong River, either through tributary transport or river bank erosion along the main stream (Fig. 10). It has also been noted that despite increasing anthropogenic activities such as deforestation and agricultural development in lower Yunnan, which have caused much soil erosion and therefore higher sediment production in the upper Mekong, major contributing source areas of sediment in the lower Mekong are located in northern Laos (Liu, 1998).

The longitudinal continuity of sediment transport along the Lancang-Mekong has been disrupted by the operation of the Manwan Dam, and is evident from the sharp decrease in sediment loads between the gauging station (Jinghong) located on the Lancang River, just upstream of the dam and the station located immediately downstream, Chiang Saen, on the Mekong River. Mean annual sediment load at Jinghong reportedly amounts to about 74 MT/yr (Plinston and He, 1999), and our estimates showed that the pre-dam sediment load at Chiang Saen was highly similar. Sediment flux at Chiang Saen in the post-dam period (1993–2000) averaged at 34 MT/year; this translated to a loss of more than 50% in sediment delivery when compared with the volume at Jinghong and the pre-dam sediment load at Chiang Saen.

The release of relatively sediment-starved, high energy water from the Manwan Dam is likely to cause channel scouring and possibly, coarsening of the bed material until equilibrium is reached and material cannot be moved by the flows (Kondolf, 1997). According to Pham et al. (2004), dam-related sediment starvation effects are already obvious for distances >600 km downstream, and with shorelines in estuarine areas at Tan Chau and My Thuan reportedly experiencing considerable erosion, the exacerbation of erosion activity is expected when more dams begin operation in the upper basin of the Mekong River.

6. Conclusion

Our results indicate that the water discharge regime of the Mekong River has been influenced by the construction of the Manwan dam in the upper stream, although the extent of influence remains small at this point. Mean discharge has remained relatively stable throughout the years, apart from periods with exceptionally high or low rainfall, or major activities like dam infilling. The seasonal discharge regime has largely remained within historical range, but the frequency and magnitude of water level fluctuations have increased considerably in the post-dam period (1993–2000).

Sediment flux has decreased on the whole, and the rate of decline in areas located immediately downstream of the dam has accelerated considerably, with sediment loads decreasing by almost half. In mid-stream areas, sediment delivery has remained stable, or even increased in the post-dam period, which may be due to the remobilization of large alluvial storages in surrounding areas. The results from our analysis of sediment load generally agree with findings from other studies on the Mekong River (Roberts, 2001; Kummu et al., 2005). The difficulty in obtaining a complete set of sediment records for the study period, however, might have resulted in some underestimation of actual sediment delivery.

A decline in sediment flux along the Lower Mekong River carries many implications downstream. The completion of the cascade dams on the Lancang would increase regulation of the flood cycle, thereby reducing the frequency and magnitude of floods, and the amount of sediment delivered downstream. Areas dependent on floods to supply nutrient-rich sediments to the soil, riparian vegetation or aquatic ecosystem could be severely deprived, and productivity of these areas might deteriorate as a consequence. Zalinge et al. (2003) have cautioned that excessive regional developments utilizing water from the Mekong River, such as cascade dams and damming of tributaries, may lead to lower downstream flood levels and excessive trapping of sediment, which will have a negative impact on the Tonlé Sap system, as the latter appears to depend on high flood levels with a correspondingly high sediment load.

Most rivers display a natural ability to maintain an equilibrium despite alterations in their hydrologic regimes. There is an imminent danger that the recent spate of hydraulic engineering developments in the upper basin of the Mekong and tributaries downstream could exceed the threshold of the Mekong River's recuperative mechanism if left uncontrolled or mismanaged. Given the importance of the sediment delivery process in the Mekong River, critical research areas requiring further study and include the impact of sediment trapping and siltation in upstream dams on the main stream and tributaries, corresponding sedimentation in fluvial-estuarine zones, flow impoundment on discharge fluctuations and water quality changes.

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Table 1. List of planned and completed hydropower projects in the Upper Mekong Basin, China.

Name of project	Installed capacity (MW)	Annual generation (GWh)	Total storage C. (million m^3)	Catchment area (km^3)	Average flow ($m^3 s^{-1}$)	Commissioning
Gongguoqiao	750	4670	510	97 300	985	2010–2012
Xiaowan	4200	18 540	15 130	113 300	1220	1993
Manwan	1500	7870	920	114 500	1230	2001
Dachaoshan	1350	7090	880	121 000	1230	2013–2016
Nuozhadu	5500	22 670	24 670	144 700	1750	2012–2013
Jinghong	1500	8470	1040	149 100	1840	
Ganlanba	150	1010	–	151 800	1880	
Mengsong	600	3740	–	160 000	2020	
Total	15 500	74 060				

Source: Mekong River Commission, 2003.

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Table 2. Sediment record availability at stations selected for sediment flux analysis.

Station	Location	No. of annual sediment records available in each period			
		1962–1970	1971–1980	1981–1990	1991–2000
Chiang Saen	20°16.4′ N 100°5.0′ E	4	5	5*	9*
Luang Prabang	19°53.5′ N 102°8.2′ E	1	–	3*	8
Nongkhai	17°52.6′ N 102°43.2′ E	–	8	10	10
Mukdahan	16°32.4′ N 104°44.2′ E	9	9	10	10
Khong Chiam	15°19.1′ N 105°30.0′ E	4	9	8*	10*
Pakse	15°07′ N 105°48.0′ E	1	–	4*	8*

* Some records were derived from water quality data (water quality monitoring in the Mekong River began in 1985).

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Table 3. Average correlation coefficient [r^2] of daily discharge (Q) and daily SSC, derived from a range of yearly r^2 values available for each station.

Location	N [Years]	r^2
Chiang Saen	14	0.73
Luang Prabang	6	0.62
Nongkhai	23	0.72
Mukdahan	32	0.67
Khong Chiam	18	0.80
Pakse	8	0.81

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Table 4. Comparison of mean discharge [Q] between pre-dam (1962–1992) and post-dam (1993–2000) periods among eight stations on the Lower Mekong.

	1962–1992		1993–2000		
Location	Q [$m^3 s^{-1}$]	N [Years]	Q [$m^3 s^{-1}$]	N [Years]	Significance [p]
Chiang Saen	Q1: 2676	30	Q2: 2653	8	0.861
Luang Prabang	Q1: 3965	31	Q2: 3924	8	0.818
Vientiane	Q1: 4443	31	Q2: 4183	8	0.295
Nongkhai	Q1: 4440	24	Q2: 4732	8	0.278
Nakhon Phanom	Q1: 6526	21	Q2: 8075	8	0.019
Mukdahan	Q1: 7508	30	Q2: 7949	8	0.372
Khong Chiam	Q1: 9298	25	Q2: 8562	6	0.309
Pakse	Q1: 9598	30	Q2: 9862	8	0.706

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Table 5. Comparison of mean sediment flux [SL] between pre-dam (1962–1992) and post-dam (1993–2000) periods among six stations on the Lower Mekong.

	1962–1992		1993–2000		
Location	S [MT/yr]	N [Years]	S [MT/yr]	N [Years]	Significance [p]
Chiang Saen	S1: 74.1	9	S2: 34.5	5	0.001
Luang Prabang	S1: 73.0	3	S2: 47.2	3	0.568
Nongkhai	S1: 74.4	17	S2: 76.1	6	0.832
Mukdahan	S1: 97.5	25	S2: 131.1	7	0.172
Khong Chiam	S1: 166.4	15	S2: 104.4	3	0.070
Pakse	S1: 151.3	3	S2: 113.5	5	0.574

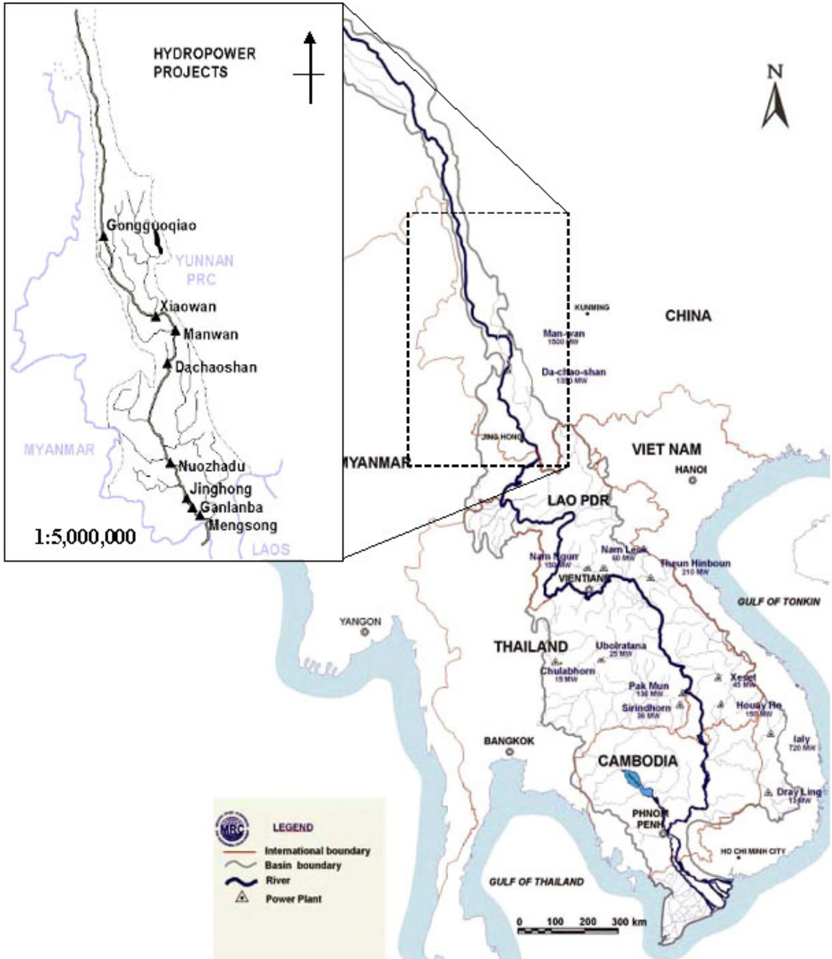

Fig. 1. Map showing China's cascade dams in Yunnan province (inset), with reference to the location of the dams in the Mekong River basin (background map).

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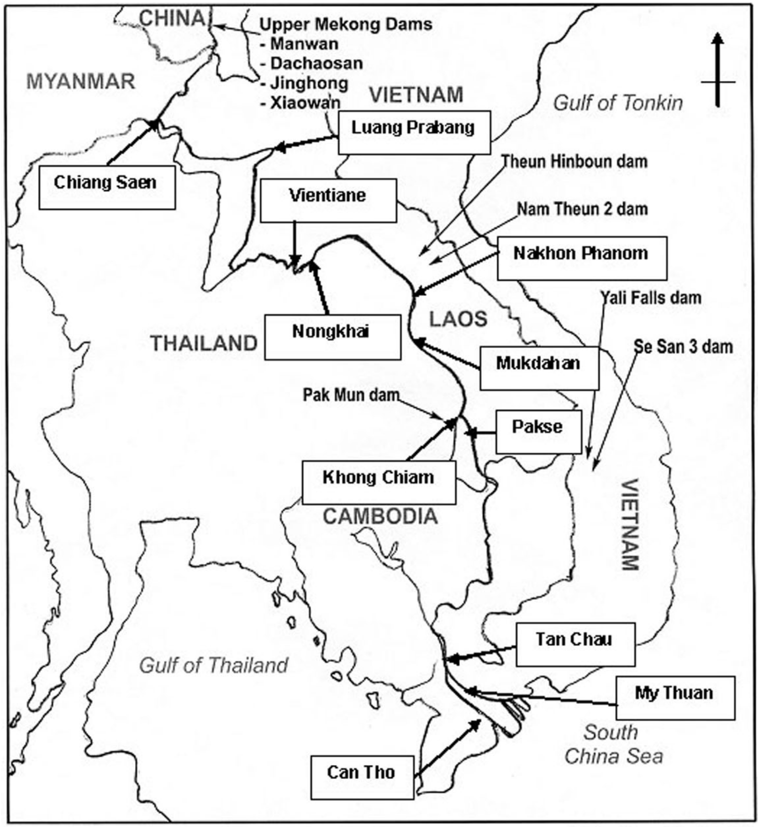

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Fig. 2. Map of the lower Mekong River basin, showing the eleven gauging stations which were used for water discharge and sediment analyses.

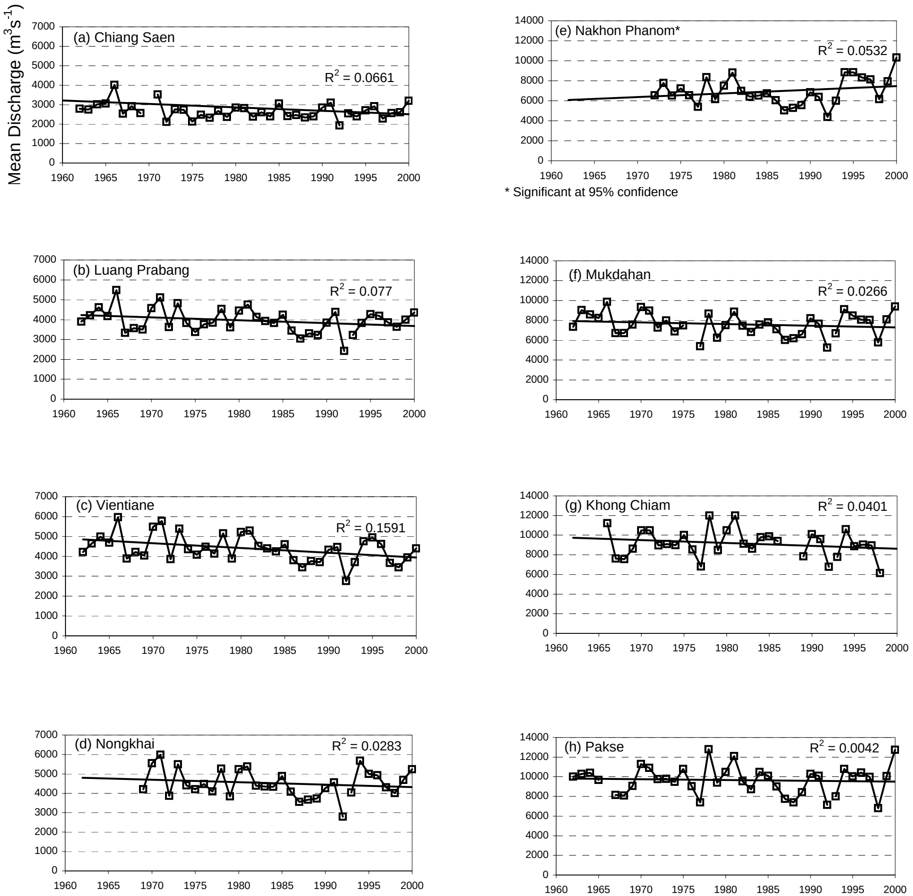

Fig. 3. Comparisons of annual streamflow records (mean discharge) at eight stations in the Lower Mekong River: Chiang Saen, Luang Prabang, Vientiane, Nongkhai, Nakhon Phanom, Mukdahan, Khong Chiam.

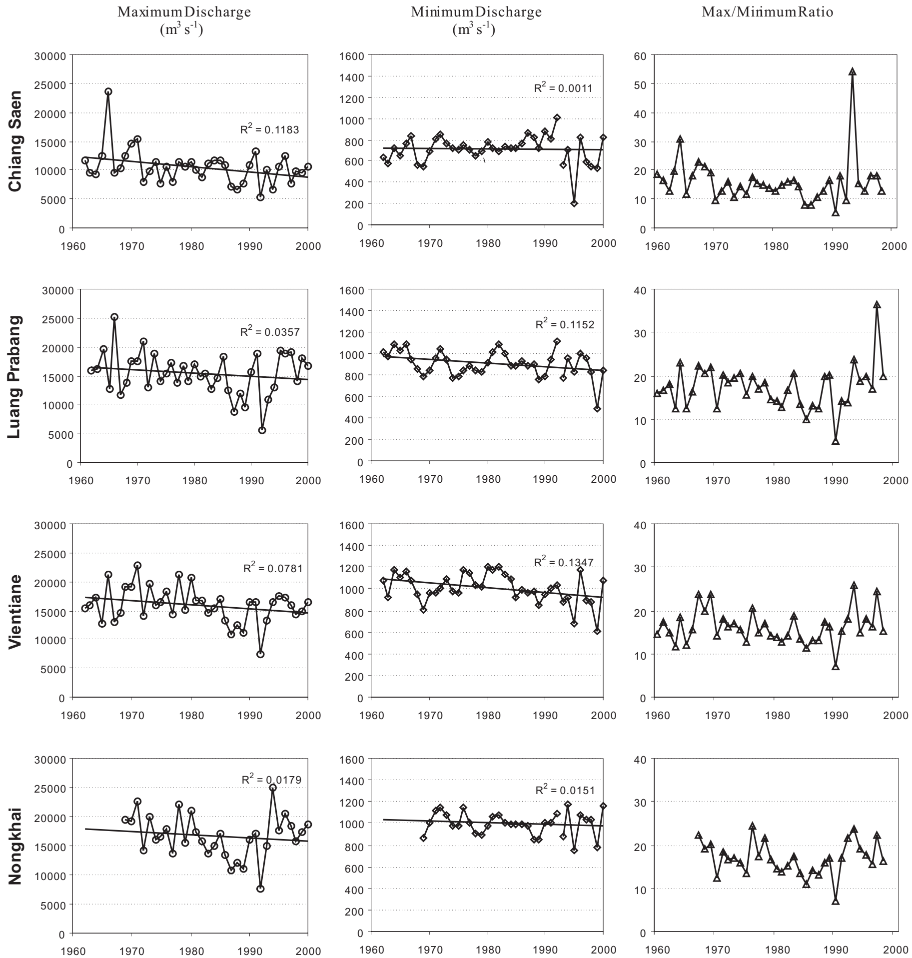

Fig. 4a. Comparisons of maximum, minimum discharge and maximum/minimum ratios at four stations (Chiang Saen, Luang Prabang, Vientiane and Nongkhai) in the upper portion of the study area.

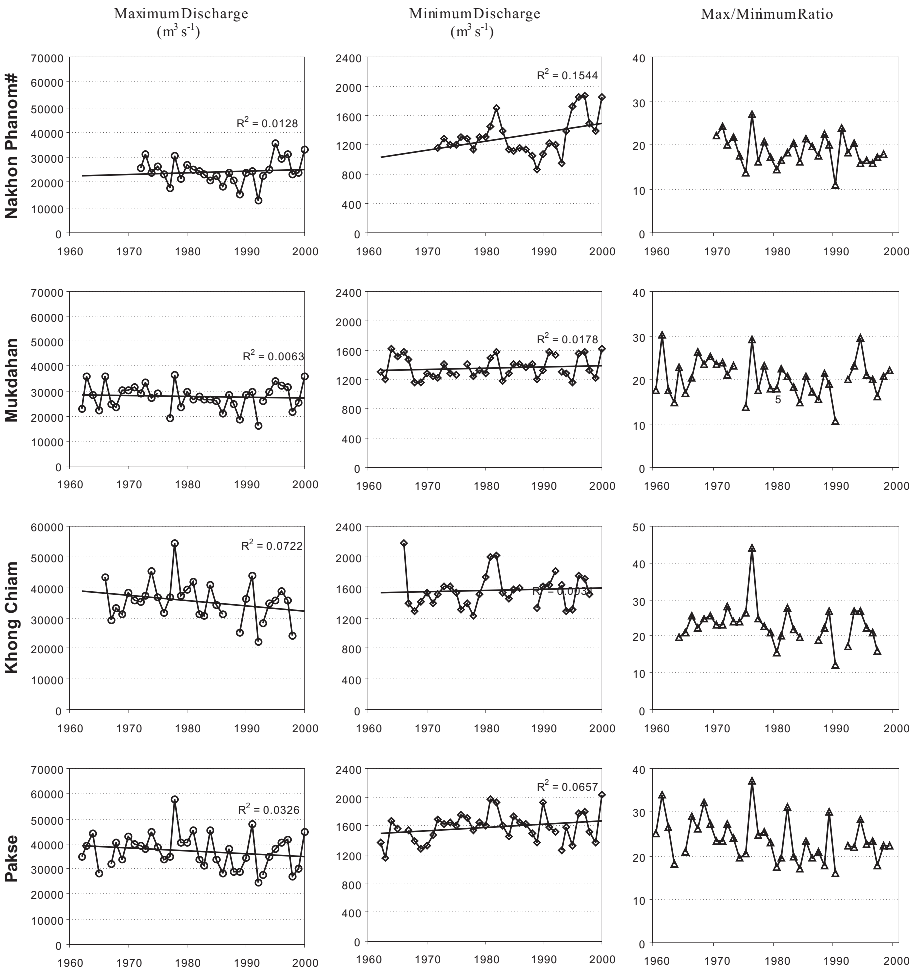

Fig. 4b. Comparisons of maximum, minimum discharge and maximum/minimum ratios at four stations (Nakhon Phanom, Mukdahan, Khong Chiam and Pakse) in the lower portion of the study area.

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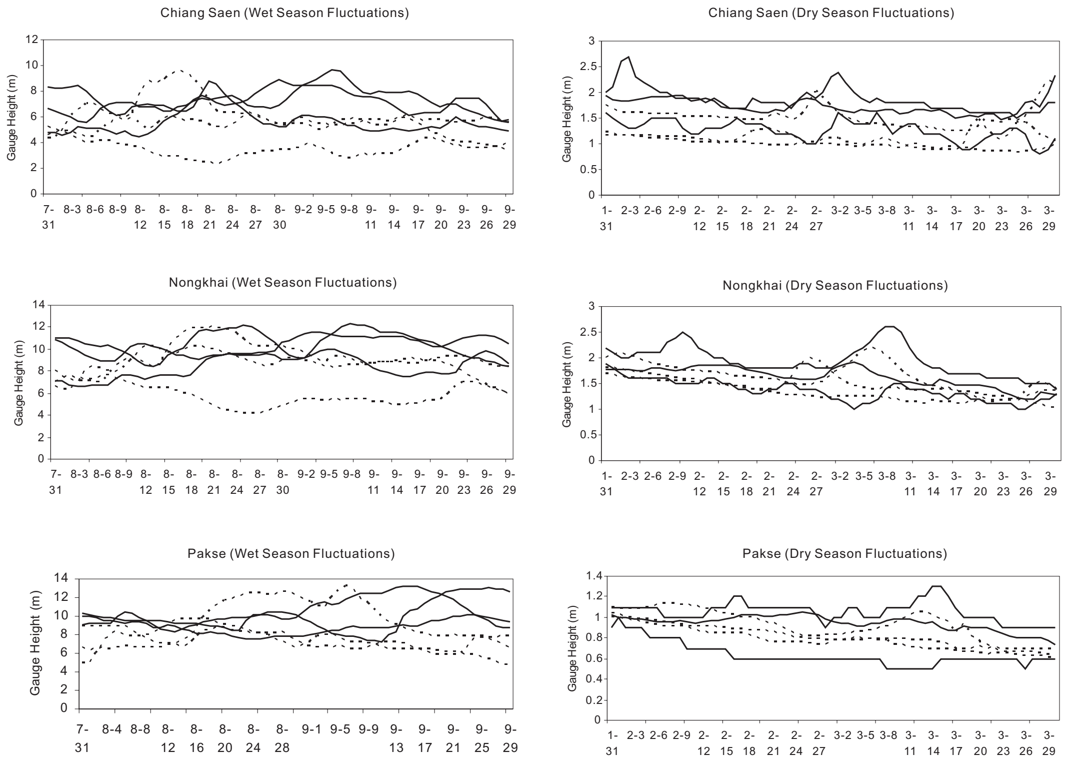

Fig. 5. Comparisons of pre- and post-dam wet season and dry season fluctuations at three stations (Chiang Saen, Nongkhai, and Pakse). Pre-dam years (1988, 1991, 1992) are depicted by dotted lines and post-dam (1996, 1999, 2000) years are depicted by solid lines.

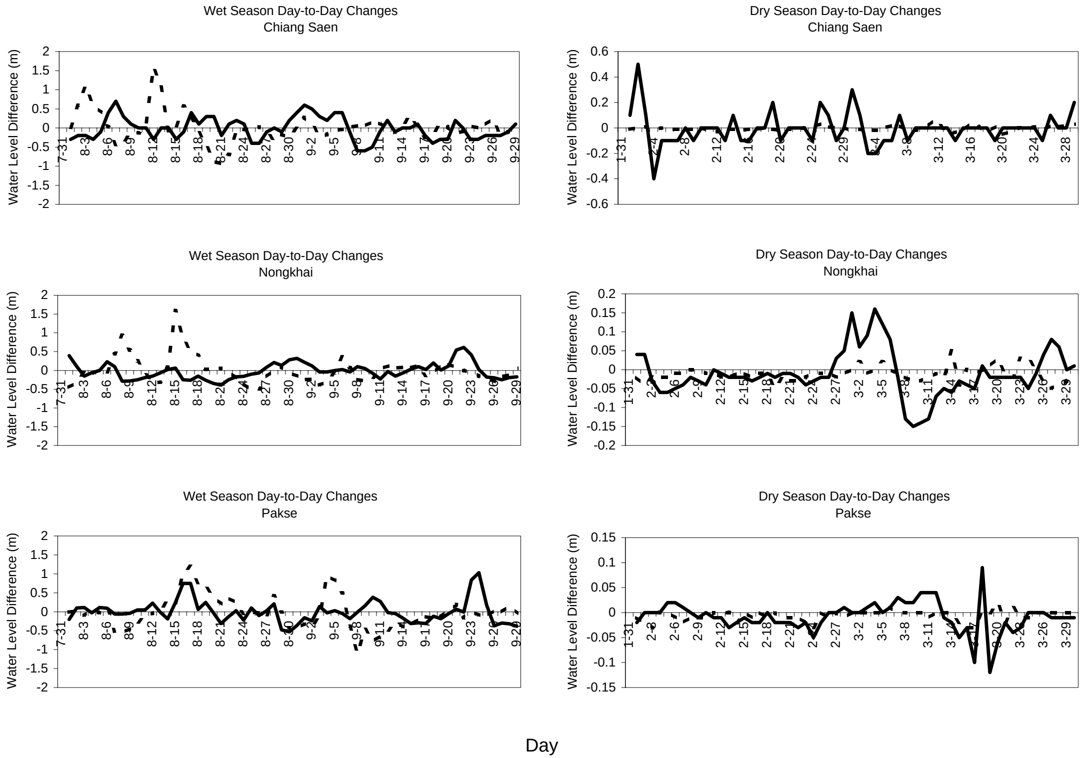

Fig. 6. Comparisons of day-to-day (water level difference between Day N and Day N-1) changes in water level between pre- and post-dam years. Day-to-day changes in the pre-dam year of 1991 are depicted by the solid line and day-to-day changes in the post-dam year of 2000 are depicted by the bold line.

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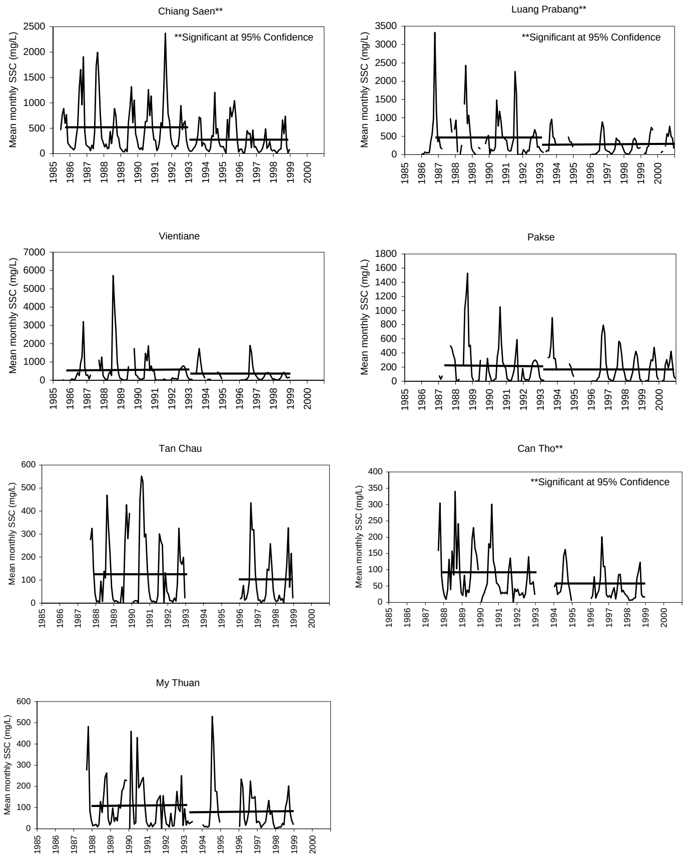

Fig. 7. Temporal changes in mean monthly sediment concentration at seven stations: Chiang Saen, Luang Prabang, Vientiane, Pakse, Tan Chau, Can Tho, and My Thuan. The horizontal lines represent the mean SSC in pre- and post-dam periods. Chiang Saen, Luang Prabang and Can Tho are significant at 95% confidence level.

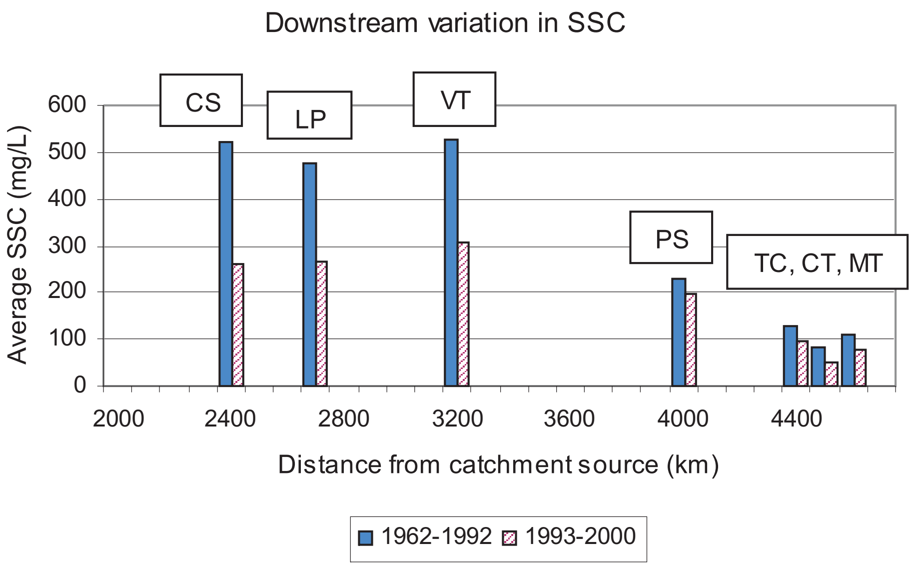

Fig. 8. Sediment concentration variation along the Lower Mekong.

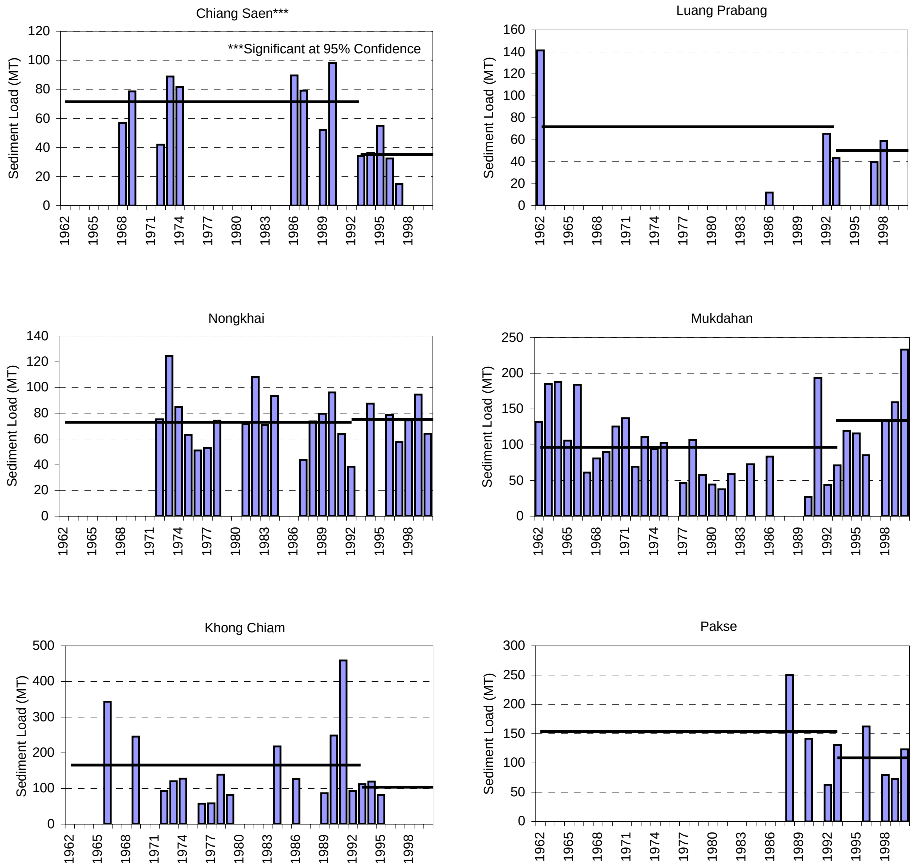

Fig. 9. Mean annual sediment load estimations and differences in sediment flux between pre- and post-dam periods. The horizontal lines represent the mean sediment load in pre- and post-dam periods. Chiang Saen is significant at 95% confidence level.

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Fig. 10. Photographs showing streambank erosion along the Lower Mekong River in Vientiane, Laos.

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